COOPERATIVE MULTI-AGENT SYSTEMS IN MOBILE AD HOC NETWORKS

Joseph P. Macker
William Chao
Myriam Abramson
Ian Downard
Information Technology Division
Naval Research Laboratory

ABSTRACT

Two important enabling but evolving technologies supporting future DoD network-centric systems at the tactical edge are, mobile ad hoc networking (MANET) and Multi-Agent Systems (MAS). Despite their value in enabling more autonomous network system operation scenarios, open research and engineering questions remain regarding robust interoperation, standardization, and design of these two technologies. We describe recent research and development that is helping to better understand crosslayer design issues within both MAS and MANET. We describe the problem area and the open software components developed to support our research. We summarize recent modeling and simulation advances in a mixed MAS and MANET scenario environment. MANET multicast approaches for interagent communications are discussed and described. Some early analysis of MAS performance is presented using a variety of interagent MANET communication models. The behavior of MAS autonomous cooperative teamwork and role allocation within disruptive and dynamic MANET environments is examined. We conclude by outlining open issues and areas of further work.

BACKGROUND AND MOTIVATION

There is planned deployment of Mobile Ad hoc Networking (MANET) type network routing technology at the battlespace forward edge or the "the first tactical mile". There is also early deployment of agent-based systems occurring now with more extensive future deployment envisioned. At present, there remains a limited understanding of appropriate architectural design tradeoffs in adapting upper layer protocols and applications in these environments. Also previous design work done with agent based networking and software has often assumed benign network behavior and highly stable infrastructures not MANET environments. Figure 1 provides a high level depiction of some of the common characteristics differentiating mainstream Internet,

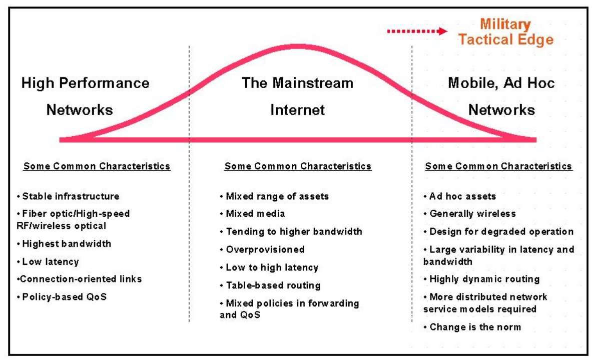

Figure 1: Network Problem Area Focus

high performance network, and tactical edge type environments. The characteristics depicted in Figure 1 emphasize why focused research should continue to be performed on tactical edge solutions including a multilayered examination of performance issues and tradeoffs.

PROBLEM FOCUS

Our technical focus is to improve design and performance of both MANET and MAS technology within dynamic network centric problem scenarios.

Some of the technical goals include the following:

- Investigate MAS design robustness in stressed, mobile network environments
- Develop network protocol enhancements and improve modeling to study behavior where needed
- Improve design tradeoff understanding by studying a combined solution (not well examined to date)

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Cooperative Multi-Agent Systems in Mobile Ad Hoc Networks**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue SW,Washington,DC,20375**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- Develop working models and software that can more easily transition

The core technical challenge of our work involves tackling cross-disciplinary issues of dynamic network protocol and multi-agent system design. Separately, MAS and MANET encompass two challenging research and engineering areas. When considered as a combined technical solution, the challenges increase due to complex crosslayer design issues and behaviors [CDCP05]. We summarize these challenges as follows:

MANET Project-Related Challenges:

- Rich taxonomy of design choices exist
- Present lack of modeling and support for interagent communication components
- Crosslayer performance design issues
- Possible agent and middleware self-organization interactions given MANET behaviors and dynamics
- Protocol scalability and robustness

MAS Project-Related Challenges:

- Rich taxonomy of design choices exist
- Lack of modeling and analysis in stressed network environments
- Adaptation of well-known strategies in disruptive MANET environments
- Designs supporting efficient inter-agent communications

PREVIOUS WORK

Ongoing research and development is being done in both MANET [B04][CM99][P01] and MAS [W02] technology areas by numerous parties. We are leveraging existing and previous work accomplishments to execute our research goals. Our previous accomplishments in this area were documented in [MAMC05]. Here we update our research approach and results and provide more detailed evaluation of cooperative multi-agent scenarios using specific MANET protocol technology.

MODELING APPROACH AND ISSUES

Figure 2 illustrates the modeling system requirements and related issues that were required in developing a framework for planned research activities. A fundamental need was to develop distributed MANET modeling capabilities in both simulation and emulation and this required the following components:

- Means of producing and controlling network dynamics and node mobility
- MANET protocol prototypes and the potential for supporting middleware system components
- Multi-agent software prototypes with flexible network interface components
- Environmental model interface to the distributed agents

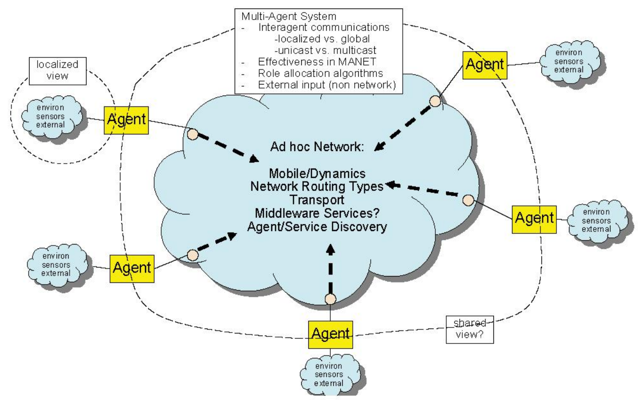

Figure 2: System Modeling Requirements

RECENT MODELING PROGRESS

Figure 3 depicts a system diagram of the modeling progress accomplished in both simulation and emulation environments. The Agent Toolkit has been recently developed to allow a more cross platform and extensible approach to be pursued in developing and enhancing java software agents placed within our test environments for

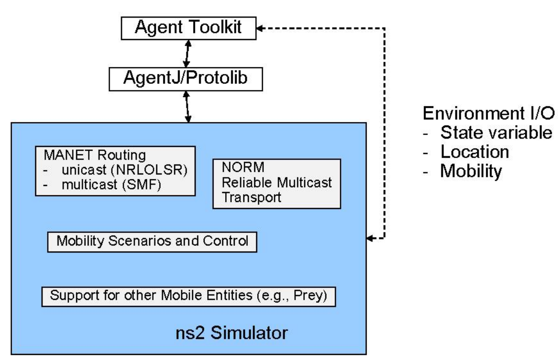

Figure 3: Key Component Modeling Diagram

experimentation. AgentJ [ADMT06] and the Protolib software components shown in Figure 3 allowed for standard java code to be ported and implemented within the NS-2 simulation environment. This has enabled more flexibility and less abstraction in simulating application layer components. This will also likely ease the inclusion of additional application agents in future efforts. As also shown in Figure 3, a distributed environmental simulation model and agent interface was added to the NS-2 environment to provide external dynamic agent stimulus and environmental modeling input. This environmental modeling channel and approach can be used to represent external sensor systems and other dynamic environmental phenomena [D04]. Recent modeling advancements go beyond previous reported results allowing us to scale our experiments and include additional capabilities such as MANET multicast routing and more complex stimulus.

RECENT MAS AND MANET STUDIES

We have constructed a number of dynamic problem solving scenarios that exercise both multi-agent system interactions and the underlying MANET communications on the move. An example of one of our primary agent team-based problem solving scenarios is a prey/predator pursuit problem. The prey/predator problem is a canonical example of agent teamwork in the literature. We adapted this problem to further study interagent behavior and teamwork performance and have included MANET routing and communications support.

A challenge in carrying out planned experiments is the actual data collection and measurement of system effectiveness. While we routinely collect and are interested in detailed protocol and network statistics, we are now also interested in measures of effectiveness for MAS. Since we are studying dynamic role allocation and agent teamwork we developed initial approaches to measure coordination quality. Given a scenario, one metric we measure is the time or number of steps it takes to complete a task or set of tasks. This provides a rough effectiveness measure of teamwork performance given a particular system design. We also gather and examine statistics in a coordination metric that measures interactions between agents performing distributed role allocation (e.g., number of messages received and role collision events).

In previous work [ACM05], we reported on the initial examination of prey/predator agent systems within simulated networks in the Repast agent-based modeling tool [NCV06]. In recent experiments, we have performed scaled studies (> 60 agents) in NS-2 simulation to examine large agent/team performance. This is done while maintaining highly detailed protocol and application modeling capturing complex behavioral and performance interactions across layers. Figure 4 shows a snapshot visualization of a 30 predator agent and 30 prey agent simulation scenario recently executed. This simulation scenario involves 60 fully functional java agents, of which 30 predator agents operate with a highly detailed MANET and IP network protocol stack model. This test also includes the operation at each node of a MANET unicast and multicast forwarding protocol to enable a self-organizing network even during periods of topology fragmentation.

Our predator/prey teamwork research approach also involves examining differing interagent communication requirements and capabilities that match various role allocation algorithms being examined. As reported in [ACM05] we used an analytical model to examine a range of role allocation strategies that require different types and levels of interagent network messaging. An early set of results demonstrated that the Distributed Constraint Optimization (DCO) approach based upon the Hungarian method [K55][PS98] outperformed other role allocation methods in simulation. We are examining this same method in a more detailed scaled network scenario with network congestion and dynamic topology disruption as additional parameters.

The basic prey/predator scenarios being used can be described as follows. The scenario is initialized with a number of predators and preys in random geographic locations. Predators sense preys using an abstracted sensor model and can communicate with other predators using MANET networking supported within the NS-2 framework. The limited sensing and wireless communication range of each predator provides both a limited environment view and a limited directly connected communication neighborhood. The scenario tasks require at minimum N predators to surround and therefore capture each prey. Although the multiple prey team and surrounding requirements establish a simple role allocation problem, the scenario is highly dynamic and uses detailed application and networking models to carry out an experiment.

Due to limited communication capabilities and ranges, interagent networking is needed to provide multihop connectivity. The predator network may also undergo unpredictable fragmentation and merging due to movement required to accomplish the task. To support research, most protocol and environment conditions are parameterized and some examples include the following:

- Sensor ranges and qualities for each prey and predator can be programmed. Special nodes may be added to have heterogeneous sensing capability.
- Differing speeds and capabilities can be established for each agent. Agents may be programmed to remain fixed if desired.
- Predator agents have limited wireless communication range that is programmable. Other environment effects and propagation models can be added to the scenario.
- A variety of MANET networking protocols and transport methods can be used by the agents during experimentation. Fragmentation and coalescing of connected networks occurs during scenarios and is supported.
- Predators must form teams of minsize = d, pursue and surround a prey to accomplish a successful capture. These parameters can be adjusted, but the default team size is four.
- High level tasks (e.g., capture) can be defined and the number of steps can be measured along with other metrics and network protocol statistics.
- Different network protocols, role allocation strategies, and external network disruption can be added to create different scenarios.

Figure 4, shows a screenshot from an example multi-agent simulation. The links drawn demonstrate the dynamic topology that is possible between the agent nodes. These dynamic links are shown between cooperative predator agents dynamically forming ad hoc networks and performing cooperative task allocation to capture prey (red denotes captured, green denotes uncaptured). Scout nodes are stationary, but contribute to predator task allocation by providing long-range prey detection.

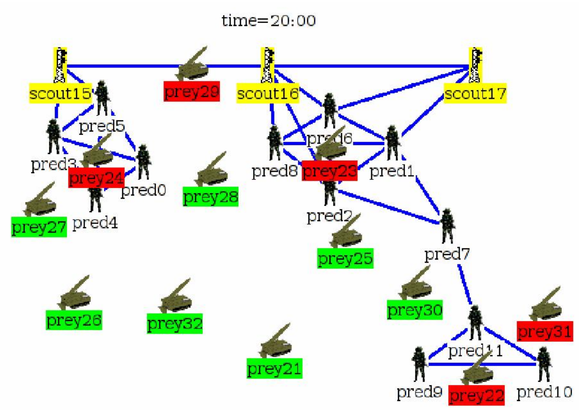

Figure 4: Multi-Agent Predator Teamwork Simulation

MANET MULTICAST FOR INTRA-AGENT COMMUNICATIONS

In order to provide enhanced network routing and network messaging mechanism for agent teamwork communications within MANETs, we are applying related research and prototype development of Simplified Multicast Forwarding (SMF). SMF research and emerging IETF specifications are discussed in [M06] and [MDC04]. SMF provides a simple multicast forwarding capability for application data flows within a MANET routing area. SMF also provides a forwarding process compatible with different neighborhood discovery protocols and optimized relay set selection algorithms. In MAS teamwork role allocation strategies, group communication and maintenance of either environmental or agent decision state is often required to be shared. SMF provides an efficient MANET networking mechanism to quickly forward this state in a dynamic environment. In one class of role allocation strategy, the distributed stochastic algorithm (DSA) [FM01], role changes are made stochastically by the agents to reduce conflicts and communicated until a consistent solution is obtained. In a second class, as in the distributed coordination optimization (DCO), the state information, or beliefs, is communicated between agents to infer their respective role using a constraint optimization method. We are examining all these classes within our research. In all these cases, while different information is being shared amongst agents there is a common requirement for communications of either state or intent. The application of SMF provides an efficient networking means of routing this group-based interagent communication within a highly dynamic network environment. While SMF is efficient if many agents require the same message, future work will study the system design tradeoffs as communication overhead and congestion conditions increase within our network scenarios.

CASE STUDY: WIRELESS NRL EMULATOR EXPERIMENTS

Factorial experiments were conducted in the wireless NRL emulator [CMW03] to study the impact of various parameters on the coordination performance of multi-agent systems in MANET. Using the prey/predator scenario described above and a fixed network density (10 nodes), the performance was measured in terms coordination [ACM05] and robustness (coefficient of variation w.r.t the median number of steps required to accomplish the goal). This robustness metric encapsulates the trade-off between performance and reliability. The communication range was allowed to vary in the 100-300 meters range to better reflect heterogeneous environments. Other parameters such as the speed of the agents were also allowed to vary. Figures 5 and 6 show comparative experimental results in different congestion environments for different role allocation algorithms. These results show how performance rapidly degrades as congestion increases.

The algorithms analyzed in these figures invoke different random processes for solving the constraint optimization problems in our prey/predator scenarios. DCO 70% will communicate status messages used to resolve conflicts only 70% of the time. In the case of DSA, a role change to resolve conflicts will occur only 70% of the time, and if a role change occurs, it will be communicated to the other agents.

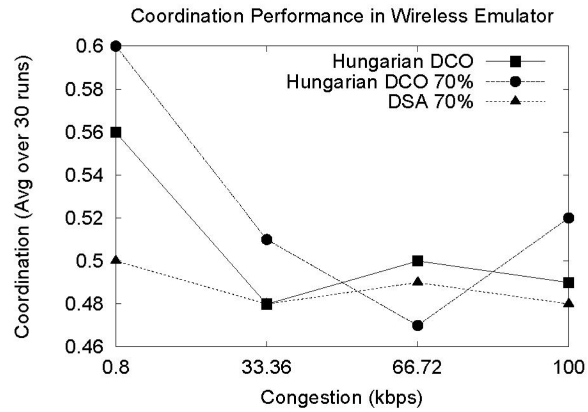

Figure 5: Comparative coordination performance at different congestion levels

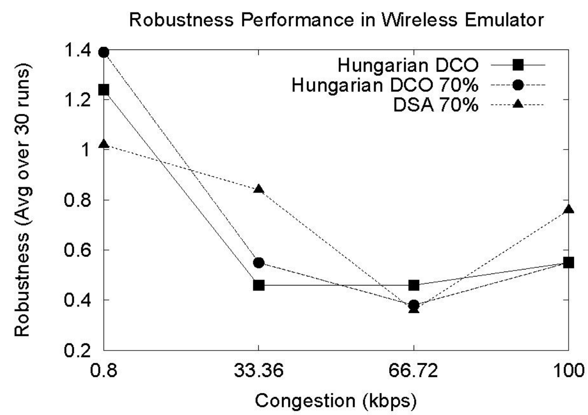

Figure 6: Comparative robustness at different congestion levels

CASE STUDY: INTERAGENT AD HOC NETWORKING VALUE

Using and applying the detailed modeling components, agent role allocation designs, and MANET protocols previously mentioned, we present Figure 7 to illustrate how communication networking can improve agent task completion. In figure 7 along the x axis we start out with a slightly fragmented physical network topology. Under these conditions, we measure the time or steps it takes for the agent group to complete the prey capturing task. In subsequent experiments, we increase the transmit power parameter or communication range achievable by predator agents, thus increasing the probability of forming a physically connected network topology. From the curve, we illustrate the variance of particular measurements and the fact that as networking probability increases the agent coordination generally improves. As network density increases we have also shown from related SMF research that we can control the amount of network traffic overhead growth for multicast data flows to reasonable levels.

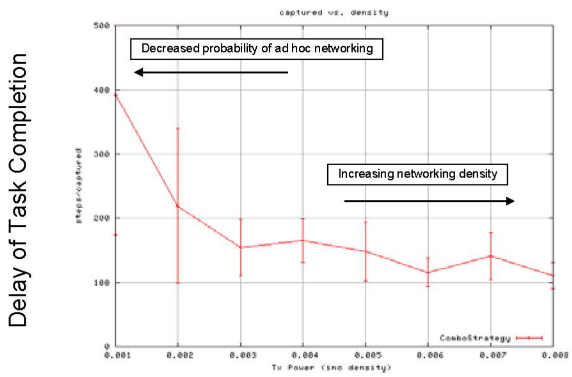

Figure 7: Task Completion vs. Network Likelihood

While this is only one basic example, it demonstrates that there are performance gains from networking agents. It also indicates that these gains can be measured in detailed modeling environments. Environmental conditions, sensor models, agent coordination strategies, and MANET protocol parameters can all be adjusted accordingly to examine different design and scenario tradeoffs. Further detailed scenarios specific studies are largely the scope of future applied work that is planned.

FUTURE WORK

Part of the challenge of studying MAS systems is developing approaches and actually measuring the effectiveness of performance. This is even more challenging within highly complex environments with competing goals. Using the outlined simulation and emulation test environments discussed here, our future work will further explore a set of use case scenarios to exercise MAS and MANET protocol performance.

CONCLUSION

We have briefly described recent research and development that is examining crosslayer issues which affect performance of MAS techniques operating within MANET environments. We summarized our recent modeling and simulation advances in achieving a mixed MAS and MANET scenario environment that can be used for further complex analysis. MANET multicast approaches for interagent communications were also briefly discussed and results from using this technique showed significant agent system improvements as networks became less fragmented and were able to take advantage of multicast. We presented further emulation and simulation analysis of MAS autonomous cooperative teamwork and role allocation within disruptive and dynamic MANET environments. While interagent communications require additional network overheard and are prone to disruption within a MANET scenario, early results from our work indicate that appropriate crosslayer design approaches can improve MAS performance. Further work has been outlined to continue more complex scenarios and the range of design tradeoffs.

ACKNOWLEDGEMENTS

We would like to acknowledge the contributions of other NRL scientists for their valuable input on work related to this project. Ranjeev Mittu, Justin Dean, Brian Adamson, and Jeff Weston all deserve acknowledgements for their contributions to various ideas and software components used in carrying out this research.

REFERENCES

[CDCP05] Marco Conti, et al. Cross-Layer Support for Group-Communication Applications in MANETs. IEEE ICPS REALMAN Workshop, July 14, 2005.

[B04] Basagni, et al, Mobile Ad Hoc Networking, Chapter 9, IEEE Press, Wiley Interscience 2004.

[CM99] S. Corson and J. Macker, “Mobile Ad Hoc Networking (MANET): Routing Protocol Performance issues and Evaluation Considerations,” RFC2501, JAN 1999.

[P01] Charles Perkins, editor, Ad Hoc Networking, Addison-Wesley. 2001.

[W02] Woolridge, M., An Introduction to MultiAgent Systems, John Wiley and Sons, Feb 2002.

[MAMC05] Macker J.P., Abramson, M. Mittu, R, Chao W., “Multi-Agent Systems in Mobile Ad hoc Network Architectures”, in IEEE MILCOM 2005 Proceedings, November 2005.

[MDC04] Macker J. P., J. Dean , W. Chao, "Simplified Multicast Forwarding in Mobile Ad hoc Networks", IEEE MILCOM 2004 Proceedings, November 2004.

[ADMT06] Brian Adamson, Ian Downard, Joe Macker, Ian Taylor, "AgentJ: Enabling Java NS-2 Simulations for Large Scale Distributed Multimedia Applications", Distributed Frameworks for Multimedia Applications conference, May 2006.

[D04] Downard, I., "Simulating Sensor Networks in NS-2", *NRL Formal Report 5522-04-10*, May 2004.

[ACM05] Abramson, M. Chao, W. Mittu, R. "Design & Evaluation of Distributed Role Allocation Algorithms in Open Environments", International Conference on Artificial Intelligence, 2005.

[M06] Macker, J.P., editor, ""Simplified Multicast Forwarding for MANET", draft-ietf-manet-smf-02.txt, March 2006, work in progress, http://www.ietf.org.

[FM01] S. Fitzpatric, L. Meertens, "An experimental assessment of a stochastic, anytime, decentralized, soft colourer for sparse graphs," First Symposium on Stochastic Algorithms: Foundations and Applications, 2001, pp. 49-64.

[CMW03] W. Chao, J. Macker, J Weston, "NRL Mobile Network Emulator," IEEE MILCOM 2003, Oct 2003.

[K55] Kuhn, H. W., "The Hungarian method for the assignment problem", Naval Research Logistics Quarterly, vol. 2, pp. 83-87, 1955.

[PS98] C. H. Papadimitriou and K. Steiglitz, Combinatorial Optimization: Algorithms and Complexity, Dover Publications, 1998.

[NCV06] M. J. North, N. T. Collier, and J. R. Vos, "Experiences creating three implementations of the Repast agent modeling toolkit," ACM Transactions on Modeling and Computer Simulation, Vol. 16, No. 1, pp. 1-25, 2006